

Application of ionizing radiation technology in agro-industrial waste: A review

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ABSTRACT

The world produces large quantities of raw materials from agriculture, aquaculture, forestry, and livestock. However, there are estimated losses of up to 50% of raw materials throughout the harvesting, slaughtering, transportation, processing, storage, and consumption stages. Due to its composition, agro-industrial waste may be slower to degrade, resulting in accumulation and negative environmental impact. Despite this, these residues retain considerable concentrations of important bioactive compounds that could be reincorporated into new formulations. Because of this, it is essential to identify applications to convert these wastes into high-value-added products. In this context, ionizing radiation has stood out as a promising technique among the current resources available for reusing waste and reducing microbial load, as it is a clean technology, does not generate additional waste, and does not raise the temperature during processing, the main limitation of conventional methods. With ionizing radiation, a new proposal for waste management emerges to reincorporate it into new products, reducing waste and reducing environmental impact. Thus, this review summarizes the most recent research on the application of nuclear energy as a viable solution and technological innovation for reusing agro-industrial waste, addressing its positive and negative effects on nutritional preservation and availability of bioactive compounds. In addition, it provides a brief analysis of the acceptability of this technology and the dissemination of information about the benefits of this process in food and waste.

1. Introduction

The 2030 Agenda elected 17 Sustainable Development Goals (SDGs) related to the realization of human rights and the promotion of sustainable development in its social, economic, and environmental dimensions, a global commitment assumed by 193 countries (UN, 2015). Sustainable development goal 2 consists in “End hunger, achieve food security and improved nutrition and promote sustainable agriculture.”

During the agro-industrial process, losses of up to 50% of raw materials are estimated, which occur mainly during harvest, post-harvest, slaughter, transportation, storage, and consumption (Arah et al., 2016; Lemes et al., 2022). Therefore, the reuse of waste is an integral part of the sustainability of the process, as it encompasses a wide range of materials with the potential to generate by-products. It should also be noted that agro-industrial waste from the food industry contains significant amounts of nutrients and bioactive compounds (extra nutritional elements, such as phenolic compounds, antioxidants, carotenoids,

anthocyanins, prebiotics, probiotics, fibers, vitamins, minerals, among others) that can serve as important ingredients in functional foods, nutraceuticals and food additives, and can also find application in the pharmaceutical, chemical and cosmetic industries (Embrapa, 2019; Madureira et al., 2020a). However, in most cases, these materials are inappropriately disposed of, causing environmental, economic, and social implications due to the lack of products with potential for reuse (Embrapa, 2018; Genevois et al., 2016).

Since the advent of X-rays, researchers have evaluated the possibility of using ionizing radiation to preserve and extend the shelf life of food products aiming at food safety. Irradiation technology is a physical process that involves exposing the target to one of three types of ionizing energy: gamma radiation, X-rays, and electron beams. The changes brought about by irradiation in food products are similar to those observed in general food processing, such as heating, washing, or freezing. However, as an advantage, irradiation can increase the shelf life of food products while preserving organoleptic and nutritional

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characteristics (Ravindran, R; Jaiswal, A, 2019). However, the consumption of irradiated foods was not a popular concept until significant advances in research provided evidence of its benefits and safety, expanding the range of applications of irradiation technology to the provision of nutritionally preserved residues for industrial reuse, incorporation as an ingredient and development of new products, contributing not only to the sustainability of the process but also to adding value to the raw material (Madureira et al., 2020a).

This review highlights the growing interest in the treatment, reuse, and application of agro-industrial waste from an environmental, social, and economic point of view. Furthermore, it highlights nuclear energy as a safe alternative and technological innovation combined with promoting sustainable development.

2. Irradiation technology: a brief history

In the middle of 1896, Minsch published a literature review on the use of irradiation in food, obtaining a reduction in the microbiological load. Irradiation gained a new look in science, with several applications and possibilities. However, it quickly came up against concerns and suspicions, mainly due to the nuclear bombardment in 1945 and the nuclear accidents that occurred throughout history. These fears were reinforced by opponents of the use of irradiation for peaceful purposes, which gained strength from misinformation and the lack of scientific work (Ehlermann, 2016a; Levy et al., 2018a,b; Josephson, 1983). Thus, it became necessary to create a joint task force of researchers in order to answer the population whether irradiated foods were safe to consume ("Wholesomeness") and their influence on nutritional content (Ehlermann, 2016b).

In the 1970s, the IFIP (International Food Irradiation Project at Karlsruhe, Germany) was launched to examine and answer these questions. The conclusions of this project were examined by a joint committee formed by the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), and the World Health Organization (WHO) in 1981, which declared that irradiated foods with up to 10.0 kGy do not promote toxicological effects or microbiological or nutritional problems since no trace of radioactivity remains in the food or the processed waste. In addition, few food samples can withstand doses above 10.0 kGy without loss of sensory qualities (Ajibola, 2020; CODEX, 1984; Ehlermann, 2016c; Xavier et al., 2018). Codex requires that any irradiated product must be labeled with the word 'irradiated' with or without the 'Radura' symbol. Despite these regulatory agencies, other countries have created their limits, such as the U.S. Food and Drug Administration (FDA or USFDA), a federal agency of the United States Department of Health and Human Services, which regulates, by 21CFR179.26, dose ranges for irradiation in food production, processing, and handling (FDA, 2023).

Decades of research have followed the use of irradiation in food, with its benefits and advantages far outweighing a few drawbacks. Now, more than ever, science is being pressured to develop and apply sustainable production processes, a commitment signed by 163 countries to be achieved by 2030 (UN, 2015). The food industry faces immense pressure to become sustainable and remain competitive. Agro-industrial waste and by-products are not part of the value chain and can negatively impact the environment. However, despite being secondary raw materials, they are a renewable resource with valuable phytochemicals such as essential oils, polyphenols, and tannins, among others (Orejuela-Escobar et al., 2021). Most of these compounds are bioactive, can be recovered from the biomass matrix, and can be used as antioxidant or antimicrobial agents (Canadas et al., 2022). Technologies such as irradiation for food safety represent a greener alternative to energy-intensive thermal processes (Chemat; Vorobiev, 2019), and efforts should be made to expand its use and acceptance in order to avoid significant economic losses resulting from the loss or contamination of food and the improper disposal of waste containing substances fit for consumption (Moreira; Castell-Perez, 2021).

3. Irradiation sources

According to the Brazilian legislation in force on this subject, food irradiation refers to the "physical process of treatment that consists of subjecting food, already packaged or in bulk, to controlled doses of ionizing radiation, for sanitary, phytosanitary and/or technological purposes" (RDC n° 21, Anvisa, 2001). Irradiation technology involves exposing food or waste to one of three types of ionizing energy: (i) gamma rays, produced from the radioisotopes cobalt-60 or cesium-137; (ii) X-rays, obtained by bombarding a high-density target with a high-power electron beam; and (iii) electron beams, generated from machine sources (Fan and Niemira, 2020). The use of cesium-137 for food processing purposes is highly discouraged due to the isotope's high solubility in water. Gamma irradiation with cobalt-60 is the preferred method of irradiation of food due to the continuous emission of rays at a predictable rate. However, there are disadvantages to a replacement of the element, both for the cost of acquisition and transportation, in addition to depending on a series of regulatory approvals. On the other hand, X-rays and electron beams are generated by machines. They are preferred in industrial plants, with the disadvantage of wear and replacement of parts, in addition to depending on a constant supply of electricity (Hallman, 2017; Fan; Niemira, 2020).

Installations must be designed to comply with radiological safety requirements, efficacy, and good handling practices. They must be equipped with qualified personnel who have appropriate professional training in compliance with the requirements of current legislation. In addition, the exposure of food or waste to the radiation source occurs for a strictly controlled time and without any direct contact with the element and, therefore, there is no risk of radioactive contamination (Bevelacqua; Mortazavi, 2020; Wang; Salvi, 2023). The unit of measurement of radiation dose in the International System of Units (SI) is the Gray (Gy). It represents the amount of ionizing radiation energy absorbed per unit mass, i.e., 1 J of radiation absorbed by 1 kg of matter (J/kg). It was adopted as part of the SI by the 15th General Conference on Weights and Measures in 1975 (Liden, 1975; Rodrigues, 2009).

4. Effects of irradiation on food and waste

4.1. Biological aspects

Gamma-ray ionizing radiation is one of the most efficient means for decontamination of food and waste (Villavicencio, 2021). Once absorbed by a biological material, gamma radiation has a direct and indirect effect on the material that receives it (Nikjoo et al., 2001). The direct effect stems from the direct interaction of radiation with essential cell structures, such as DNA/RNA (most pronounced in single-stranded structures), proteins, and membranes. Not only does this disrupt cellular function, but it also incapacitates microorganisms from replicating or regenerating. The indirect effect, in turn, results from the interaction of radiation with the aqueous medium of the cells, generating highly reactive free radicals, a reaction commonly known as radiolysis. These free radicals will interact with the other cellular components of the microorganisms, such as the organelles present in the cytoplasmic matrix, causing widespread damage that corresponds to 70% of all radiation effects (Fanaro et al., 2015; Moreira; Castell-Perez, 2021). As irradiation can be applied to packaged foods, the possibilities of re-infestation and recontamination are limited (Diehl, 2002; Villavicencio et al., 2007; Farkas; Mohácsi-Farkas, 2011; Tripathi et al., 2023).

4.2. Nutritional aspects

Irradiation is considered a "cold" process because it does not involve a significant increase in the temperature of the irradiated samples. The first advantage conferred by this property is the possibility of treating chilled, frozen, or heat-sensitive materials. Food and waste products that undergo irradiation processes have a longer shelf life than thermal

processing while retaining their flavors and aromas, which are diminished by conventional processing methods that employ some form of heating. On the other hand, cooling methods, such as freezing, have the advantage of causing minimal changes in the sensory characteristics and nutritional properties of food and residues; however, when compared to heat treatments, they are considered mild, as their impact on the increase in shelf life is low (Mostafavi et al., 2012; Eustice, 2017). The chemical changes in irradiated foods are small, and few nutritional deficiencies have been reported; however, some vitamins are sensitive to irradiative degradation, such as vitamins C, E, A, and B12, although, at the permitted doses (up to 10 kGy), these reductions are small in relation to the natural variation in vitamin content in these foods (Kilcast, 1994; Ravindran; Jaiswal, 2019). Irradiation technology, therefore, emerges as a promising strategy by combining the increase in shelf life with the nutritional preservation of treated food and waste. It also avoids dependence on chemical methods, such as food additives, commonly used in industrialized products (Nishihira, 2020).

4.3. Examples of applications in the food industry

Several studies have been conducted on the use of irradiation in food and waste products, with the dosages used varying according to the objectives for which they are intended. Fig. 1 schematically presents the main applications of ionizing radiation in foods and agro-industrial residues. This technology has been widely applied to different

matrices, such as fruits, vegetables, cereals, meats, seafood, and by-products of the food industry. Among the main effects are the elimination of pathogenic microorganisms, the reduction of microbial and spoilage fungal activity, the inhibition of sprouting, the disinfection of insects and parasites, the extension of shelf life, and the decontamination of agro-industrial residues. By ensuring safer and longer-lasting products, irradiation not only reduces post-harvest losses but also strengthens agricultural competitiveness and aquaculture supply chains, thereby promoting sustainable growth in these sectors.

In the case of food irradiation, low doses are considered those up to 1 kGy, medium doses from 1 to 10 kGy, and high doses above 10 kGy. This classification corroborates with data available in the literature, where Ehlermann (2016c) reported that with low doses, it is already possible to achieve the phytosanitary safety of fruits, vegetables, grains, and cereals. Medium doses, in turn, provide shelf-life extension, inactivation of pathogenic bacteria (in some animal and plant products), and improvements in the technological properties of food. On the other hand, high doses are used in industrial decontamination and sterilization processes; however, for food, they are pretty restricted, such as pre-prepared meals, hospital diets, sterilized astronaut diets, and some spices (Table 1) (FDA, 2023; Madureira et al., 2021; Sahoo et al., 2022; Villavicencio, 2021)

Studies in the literature show that most of the desired effects in food, such as sprout inhibition, delay in the maturation process, disinfection of insects, and reduction of microbial load, can be obtained at low and

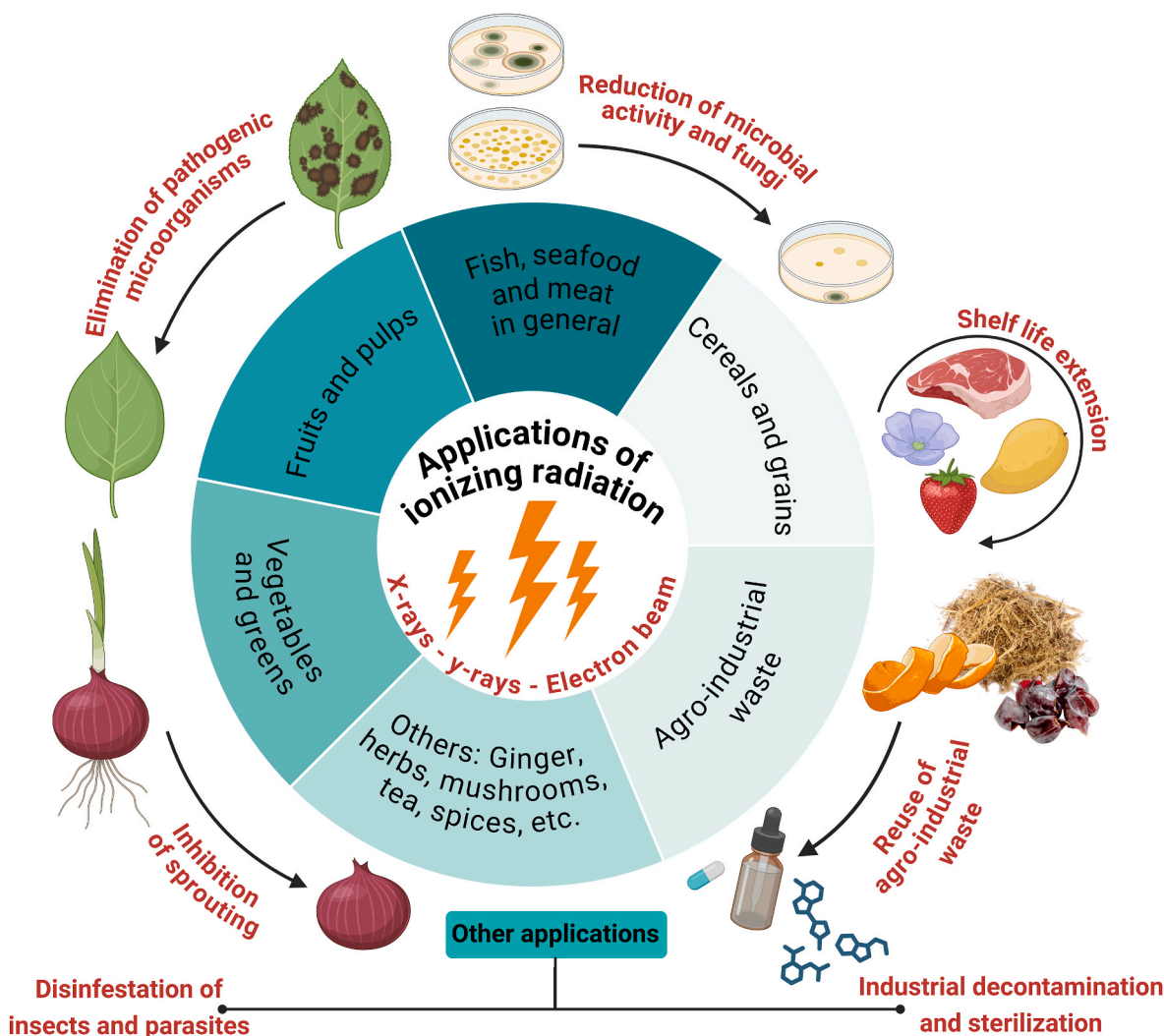


Fig. 1. Scheme of the applications of ionizing radiation in different food matrices. Created with BioRender.com.

Table 1

Applications, doses, and effects of irradiation on food products.

Applications and doses (kGy)	Products	Effects	Benefits	References
Sprout (0.25-0.99)	Potatoes, onions, garlic, ginger, yams, and others	Sprout inhibition	Longer storage time	Buwaneswaran et al., 2024; Villavicencio (2021)
Insect disinfestation (0.30-1.0)	Cereals, beans, dried and fresh fruits	Insect elimination	Reduction of losses, chemicals and insects that can spread	Colletti et al., 2024; Villavicencio (2021)
Parasite disinfestation (0.30-1.0)	Dried fish, dried meat, raw fish, fresh pork	Reduction of pathogenic organisms*	Prevents contamination when consuming raw or undercooked food	Colletti et al., 2024; Villavicencio (2021)
Delay of the physiological process (0.70-1.0)	Fresh fruits and vegetables	Reduction or inhibition of maturation	Longer shelf life	Colletti et al., 2024; Bhatnagar et al. (2022); Villavicencio (2021)
Shelf life extension (2.5-4.5)	Fresh fish, strawberries, fresh mushrooms, and others	Reduction of microorganisms, delay of degradation process and preservation of compost	Longer shelf life	Colletti et al., 2024; Villavicencio (2021); Mondal and Akhtaruzzaman, 2024; Bhatnagar et al. (2022); Fernandes et al. (2012)
Elimination of pathogenic microorganisms (4.5-7.0)	Seafood, poultry and red meat, egg products, Camembert cheese	Elimination of non-spore forming pathogens	Greater control of fresh, chilled, and frozen meat	Villavicencio (2021); Joshi et al. (2023); Mondal and Akhtaruzzaman, 2024
Improvement of technological properties (2.5-7.0)	Grapes, dehydrated fruits and vegetables, green tea, wine, and others	Improvement in nutritional and organoleptic properties	Improves juice and wine production, rehydration, and cooking time of vegetables	Colletti et al., 2024; Villavicencio (2021); Štajner et al. (2007); Gupta et al. (2015)
Reuse of agro-industrial waste (1.0-20.0)	Waste from fruits, vegetables, grains, olive pomace, and others	Depolymerization, extractability and bioavailability	Increased quantity and extraction of bioactive compounds	Madureira et al. (2020b); Hussain et al. (2016); Pereira et al. (2015)
Spores (7.0-10.0)	Dried herbs and spices, condiments, and dehydrated vegetables	Spore elimination	Longer shelf life	Villavicencio (2021); Balaji et al. (2024)
Industrial decontamination and sterilization (above 10.0) ^a	Herbs and spices, condiments, enzyme preparations, natural gums, meats, seafood, sausages, sterilized diet	Significant reduction in microbial load. Significant loss of nutrients ^b	Extended shelf life	Villavicencio (2021)

^a Examples: *Trichinella spiralis*, *Taenia spp.*, *Entamoeba histolytica*, *Toxoplasma gondii*.^b There are losses in the nutritional properties of foods processed with doses above 10 kGy (such as the sterilized astronaut diet).

medium-low doses of irradiation (Shah et al., 2014; Sahoo et al., 2022). The small size and low moisture content of viruses ensure they are more resistant to irradiation than bacteria (Doyle, 2010). Doyle's work gathered data showing that the effectiveness of irradiation on some viruses in food, such as polio, hepatitis A, and rotavirus viruses in oysters, is achieved at doses of 2.94, 2.0, and 2.4 kGy, respectively. Doses of 3 kGy provided a reduction of 1 log of hepatitis A virus in lettuce and strawberries. For Newcastle disease in eggs, the dose of 2 kGy was sufficient for the inactivation of the virus. In relation to low pathogenic avian influenza, effectiveness is achieved with 1.6 kGy in fresh egg whites and 2.6 kGy in poultry meat. There are numerous applications of ionizing radiation in microorganisms. The review prepared by Xavier et al. (2018) presents a list of studies on the control of microorganisms in products of animal origin using radiation technology.

Memon and Gat (2020), studied the effect of sodium benzoate and gamma irradiation (0.5, 1.0, and 1.5 kGy), alone or in combination, on freshly cut green onions. They showed that the 1.5 kGy dose in combination with sodium benzoate helped to promote color, preserve firmness, and reduce microbial load and moisture content, demonstrating to be an effective treatment in extending shelf life and maintaining its nutritional and sensory quality for up to 16 days at 5 °C. In addition, the study by Štajner et al. (2007) reported that average irradiation doses between 1 and 10 kGy significantly increased soybean seeds' total phenolic and tannin content. A greater accumulation of phenolics and flavonoids was also observed in the irradiation of fresh mushrooms, but for some varieties, there was no significant difference in these compounds (Fernandes et al., 2012).

Higher doses are mainly used in dehydrated products, which is justified by the interaction of water molecules with ionizing radiation, leading to the formation of free radicals and interactions/reactions with the irradiated material that are harmful to consumption. Fanaro et al. (2015), in a study with green tea, found that there is a proportional relationship between the increase in the water activity and the decrease in the irradiation dose necessary to reduce microbiological

contamination, without interfering with the content of main flavonoids and antioxidant activity at doses of up to 5.0 kGy.

As presented, food irradiation has considerable advantages in reducing the microbiological load and increasing the shelf life of food, while preserving the organoleptic and nutritional properties (Villavicencio, 2021). In addition, the use of irradiation as a technological application to improve nutritional qualities has proven to be an interesting process that can be extended to agro-industrial waste, since these by-products (peels, pulp, seeds, and stones) often have more bioactive compounds than the product of primary interest itself (Ben-Othman et al., 2020). Phenolic compounds, for example, are found predominantly in by-products rather than in edible portions, as they tend to accumulate in the dermal tissues of the plant body due to their potential role in protecting against UV rays (Babbar et al., 2015). Next, the main studies with agro-industrial residues and the contributions of ionizing radiation technology in the processes of depolymerization, bioavailability, and extractability of bioactive compounds will be presented below.

5. Bioactive compounds in agro-industrial waste

Agro-industrial waste from the food industry has significant amounts of bioactive compounds (extra nutritional elements, such as phenolic compounds, carotenoids, prebiotics, probiotics, fibers, vitamins, and minerals, among others) (Vuong, 2017). Each of these compounds has its importance and function in the body, but the most extensively studied compounds are phenolics, one of the most diverse and extensive groups of metabolites, with a wealthy family of phytochemicals divided into diverse subclasses: flavonoids, phenolic acids, coumarins, stilbenes, and tannins. These compounds act as chemopreventive agents and inhibitors of oxidative stress; however, they are not present in abundance in the regular diet and need to be consumed mainly from plant sources (roots, stems, leaves, flowers, and fruits) because they contribute to antioxidant, antimicrobial, antitumor and anti-inflammatory properties

(Daayf et al., 2003; Biesalski et al., 2009; Da Silva et al., 2024). Carotenoids are compounds notable for their wide natural distribution, diverse chemical structures, and varied functions. Examples are alpha-carotene, beta-carotene, lutein, zeaxanthin, and lycopene. Although they are micronutrients, present at very low levels, carotenoids are among the most important food constituents because they are bioactive substances with antioxidant action, beneficial effects to fight diseases and also precursors of vitamin A (Mercadante et al., 2017; Hacke et al., 2022).

Although there is no ideal method to extract these compounds, ionizing radiation technologies have been shown to improve the extraction yield of bioactive compounds from some wastes, a promising alternative for the breakdown of complex compounds into bioactive compounds that are easily assimilated, facilitating their absorption by the body and, consequently, their bioavailability and bioaccessibility when consumed. In the last decade, several studies have been published on the extractability and improvement of the bioactive properties of chemical compounds in irradiated food and agro-waste, allowing them to be incorporated into food products and contributing to the development of functional foods (Madureira et al., 2020a; Levy; Villavicencio, 2020).

5.1. Mechanistic effect of ionizing radiation

The residues originating from agro-industrial processes are composed, for the most part, of plant biomass. This biomass results from the accumulation of plant cells present in different plant structures, such as peels, leaves, stems, and seeds, which remain after activities like harvesting, processing, or product extraction. Due to their composition rich in polysaccharides and other structural biopolymers, these residues represent a strategic resource for the development of technologies aimed at valorizing and sustainably utilizing them.

Ionizing radiation exerts its influence on plant cells through two main mechanisms: the direct effect and the indirect effect (Bhatnagar et al., 2022). In the direct effect, this radiation directly induces the destruction of cell components such as the cell wall, organelles, soluble metabolites in the cytoplasm, and DNA, while in the indirect effect, free radicals and reactive species—including hydroxyl radicals ($\bullet\text{OH}$), hydrogen peroxide (H_2O_2), superoxide anion ($\text{O}_2\bullet^-$), hydrogen atoms, and hydrated electrons from water radiolysis—act on the cellular components (FAN; WANG, 2021). Furthermore, cell damage may include reactive nitrogen species (RNS), which represent an additional class of reactive molecules, expanding the impact of ionizing radiation on cells, especially when combined with ROS (Leach et al., 2001; Wardman, 2009).

The plant cell wall is a complex structure composed mainly of polysaccharides, among which cellulose and hemicellulose stand out, responsible for providing resistance and mechanical support to the cells. Associated with these carbohydrates, lignin is deposited primarily in supporting tissues, interweaving with the polysaccharide matrix and contributing to the strengthening and waterproofing of the cell wall (HEREDIA et al., 1995). In addition to its biological function, it has attracted technological interest in areas such as food, pharmaceuticals, and biomaterials; however, the structural complexity of these substances makes biomass resistant to degradation, which represents a challenge for modification and utilization processes. In this context, the application of ionizing radiation emerges as an effective tool for promoting chemical alterations, such as the depolymerization of polysaccharides and lignin, which facilitates their processing and use (Cieřla, 2017; Thakur et al., 2024).

Plant cells can be viewed as compartmentalized systems of bioactive compounds, in which phenolics play key roles in both defense and structure, and can be found in extractable (free-soluble) and non-extractable (insoluble or bound) forms. The concept of extractable vs. non-extractable polyphenols is related to their extractability in aqueous and organic solvents, although non-extractable polyphenols can also be

released after appropriate chemical or enzymatic hydrolysis (Fernandes et al., 2023). However, chemical processes rely on strong reagents, while enzymatic methods can be quite costly (Cieřla, 2017).

In their free and soluble form, these compounds are present in the cytoplasm, ready to interact with reactive species and regulate metabolic pathways (Kumar; Pandey, 2014; Daryanavard et al., 2023). The free-soluble form is not restricted to the cytoplasm; free phenolic compounds are also stored in organelles such as vacuoles, mitochondria, or other vesicles. Studies indicate that most soluble phenolics are stored in plant vacuoles, where the acidic environment facilitates their retention and stability, preventing physical or chemical interaction with other plant macromolecules (Shahidi; YEO, 2016). The increase in phenolic compounds observed is not always attributed to biosynthesis; the greater extractability of phenolics may be related to cell membrane rupture and the release of bound phenolics, resulting in higher extractability and improved bioaccessibility. This differs from biosynthesis, which is proposed as a dual stress-response mechanism involving ATP, ROS, and enzyme activation and deactivation.

In contrast, non-extractable phenolics are firmly embedded in the cell wall, especially in lignin, whose aromatic polymeric architecture constitutes the largest reserve of structural phenolic compounds (Jung et al., 2015). Hemicellulose, when bound to phenolic acids such as ferulic and *p*-coumaric, represents an additional source of bound phenolic compounds, acting as a bridge between cellulose and lignin (Wang et al., 2018). Lignin is composed of three phenylpropane units: *p*-hydroxyphenyl (H), guaiacyl (G), and syringyl (S), which are derived from three traditional monolignols—*p*-coumaryl, coniferyl, and sinapyl alcohol, respectively—and contain various methoxy, carboxylic, phenolic, and carbonyl functional groups. When subjected to chemical and/or physical treatments, the lignin component is depolymerized to form monomeric and oligomeric phenolic compounds. Lignin degradation mainly produces 2-methoxyphenol (guaiacol) and syringol. Further decomposition of guaiacols leads to the formation of phenol, cresols, and vanillin, among others (Basafa; Hawboldt, 2023).

Fig. 2 presents an integrated view of the effects of ionizing radiation on plant cells, showing how both indirect effects—mediated by water radiolysis and the consequent generation of reactive species (Fig. 2A)—and direct effects—resulting from the incidence of radiation energy on structural components such as the cell wall (Fig. 2B), organelles (Fig. 2C), and DNA (Fig. 2D)—act in a complementary manner. These processes result in greater extractability of bioactive compounds bound to the structural matrix and organelles, as well as the modification of cytoplasmic compounds and increased bioavailability.

It is important to highlight that the medium in which agro-industrial residue is irradiated determines the dose required to achieve the desired depolymerization. In the work of Cieřla (2017), it was reported that, to obtain the same level of depolymerization, it was necessary to irradiate solid polysaccharides with an absorbed dose about thirty times higher compared to irradiation carried out in aqueous solution. This occurs because irradiation in the solid state involves the direct effects of radiation, while irradiation in water propagates indirect effects from radiolysis products and their subsequent reactions with the polymer.

The compartmentalized nature of the plant cell makes water the main target of ionizing radiation, leading to radiolysis as the initial step of chemical modifications. The indirect mechanism of ionizing radiation, mediated by water radiolysis, plays a decisive role in the chemical transformation of plant residues. The initial generation of hydroxyl radicals ($\bullet\text{OH}$), hydrated electrons (e_{aq}^-), and hydrogen radicals ($\bullet\text{H}$) creates an environment that is simultaneously highly oxidative and reductive, capable of inducing profound modifications in the architecture of polysaccharides. While $\bullet\text{OH}$ acts as a powerful oxidizing agent, promoting the cleavage of covalent bonds and introducing carbonyl and carboxyl groups into the chains, e_{aq}^- and $\bullet\text{H}$ perform reducing functions that also contribute to the structural instability of biomass (List et al., 2023).

This duality of chemical reactivity results in a balance of degradation

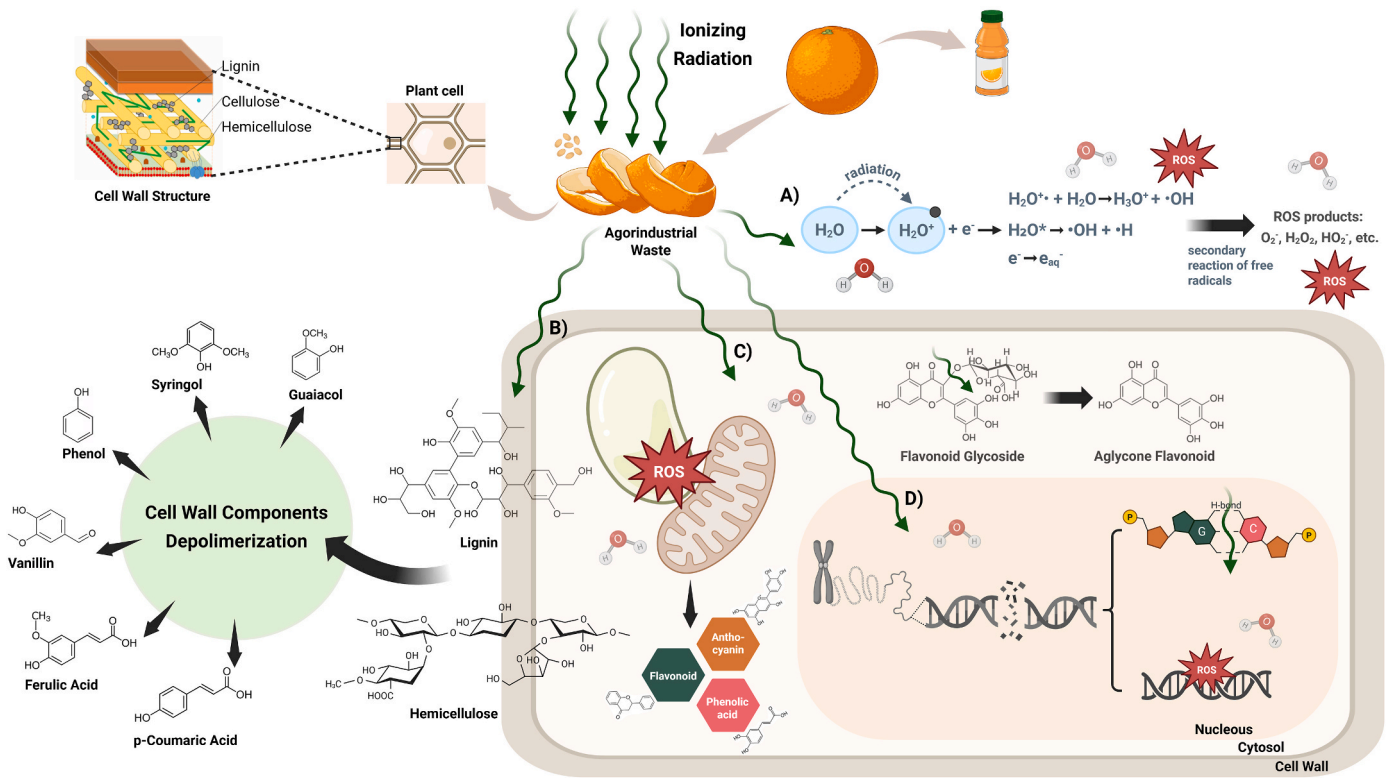


Fig. 2. A mechanical overview of the direct and indirect effects of ionizing radiation on plant cells. (A) Water radiolysis process and ROS generation; (B) Depolymerization of structural constituents of the cell wall; (C) Effects on organelles and free bioactive compounds in the cytoplasm; (D) Genomic alterations induced in the cell nucleus. Created with BioRender.com.

and functional modification reactions, which translates into loss of crystallinity, polymer fragmentation, and increased availability of functional groups. The impact of this process is reflected in greater bioavailability of compounds, higher enzymatic accessibility, and potential applications of agro-industrial residues in areas such as biopharmaceuticals, biomaterials, and food formulations (Yuan et al., 2021; Meena et al., 2025). Table 2 summarizes the main primary and secondary species from water radiolysis, along with their origin, predominant functions, and classification regarding their ROS character.

5.2. Ionizing radiation in agro-industrial waste

Almond shell (*Prunus amygdalus*) is an agricultural by-product that is a source of phenolic compounds. Harrison and Were (2007) reported that irradiation of peel extracts from 4 to 12.7 kGy increased total phenolic content and antioxidant activity by up to 45% compared to the non-irradiated control. In the same year, the work of Pérez et al. (2007) showed a 35% increase in the content of phenolic compounds in extracts of dried rosemary leaves (*Rosmarinus officinalis* L.) irradiated at 30 kGy compared to non-irradiated control samples. Amilcar et al. (2011) evaluated the influence of gamma irradiation on the antioxidant potential of chestnut fruits and shells (*Castanea sativa* Mill.), pointing to a beneficial effect regardless of the dose used (0.27 ± 0.04 kGy or 0.54 ± 0.04 kGy) (Antonio et al., 2011). *Curcuma alismatifolia* (Zingiberaceae) leaves treated with gamma radiation increased the total phenolic content by 32.7% (15 kGy) and 51.4% (20 kGy), while for total flavonoids there was an increase of 29.8% (15 kGy) and 78.3% (20 kGy) (Taheri et al., 2014).

Khattak and Rahman (2016) evaluated the effect of ionizing radiation on some quality attributes and biological properties of *Ziziphus mauritiana* leaves. The results showed that treatment with 12.5 kGy of gamma radiation led to a higher concentration of bioactive compounds, especially phenolics and flavonoids, in addition to improving the

Table 2
Water radiolysis: species, origins, functions and ROS (Reactive Oxygen Species).

Class	Species	Origin/Main Reaction	Function/Condition	ROS
Primary	•OH (hydroxyl radical)	Ionization/excitation: $H_2O^{+*} + H_2O \rightarrow \bullet OH + H_3O^+$	Very powerful oxidant, attacks covalent bonds	Yes
	•H (hydrogen radical)	$H_2O^* \rightarrow \bullet H + \bullet OH$ or secondary recombination	Reducing agent, can react with O_2	No
	e_{aq}^- (aqueous electron)	Solvation of free $e^- \rightarrow e_{aq}^-$	Very strong reductant, reacts with O_2	No
	H_3O^+ , OH^- , H^+	Immediate ionic products	Alter local pH	No
Secondary	H_2O_2 (hydrogen peroxide)	$\bullet OH + \bullet OH \rightarrow H_2O_2$	Less reactive oxidant, accumulates in the medium	Yes
	H_2 (molecular hydrogen)	$\bullet H + \bullet H \rightarrow H_2$	Inert product, escapes the system	No
	$O_2^{\bullet -}$ (superoxide radical)	$e_{aq}^- + O_2 \rightarrow O_2^{\bullet -}$	Reductant, conjugate base of $HO_2\bullet$	Yes
	$HO_2\bullet$ (peroxyl radical)	$\bullet H + O_2 \rightarrow HO_2\bullet$	Moderate oxidant	Yes
	HO_2^- (peroxide anion)	$HO_2\bullet \rightleftharpoons H^+ + O_2^{\bullet -}$ (pH > 5)	Basic form of $HO_2\bullet$	No

(*) indicates a molecule in an electronically excited state.
(•) represents a free radical, that is, a chemical species with an unpaired electron.

biological properties of the leaves, such as antibacterial and antioxidant activity (KHATTAK; Rahman, 2016). Apple pomace is an attractive source of phenolic compounds. The work of Ito et al. (2017) revealed

that irradiation of apple pomace flour at 1 kGy was able to increase the extractability of individual and total phenolic compounds, as well as the antioxidant potential. In a study with raspberries, an increase in total phenolic content was observed as a function of the radiation dose (Verde et al., 2013). Madureira et al. (2017) revealed that gamma radiation at 100 kGy was able to increase between 34% (reduction of DPPH) and 62% (bleaching of β -carotene) the antioxidant activity in effluents generated from the cork cooking (*Quercus suber* L.), a raw material used in a wide variety of products ranging from engine gaskets to wine stoppers.

Madureira et al. (2020b) reported that doses of up to 22 kGy in olive pomace improved the extraction capacity of the main phenolic compounds present in the matrix by 2.4 times. However, it was observed that the dosage of 10 kGy presented the highest amount of total phenolic compounds. This result can be justified due to the depolymerization process that helps in extractability, revealing that there is a limit to the application of the irradiated dose to preserve the compounds. Rao (2020) showed that macadamia nut residue irradiated by gamma radiation (0 – 7.5 kGy) is even richer than the nut in micronutrients such as Ca, K, Mn, Mg, Cu, and Zn. Bashir et al. (2017) reported that gamma radiation treatment of whole wheat flour and starch resulted in the modification of their physicochemical properties, such as decreased paste parameters, increased freeze-thaw stability, water solubility, and water absorption capacity compared to enzymatic and chemical treatments.

Despite the studies demonstrating the increase in the amount of bioactive compounds and improvement in the general quality of the product, some authors did not detect such phenomena at doses up to 5 kGy, but only that irradiation conserved such compounds, avoiding possible degradation, which is still considered an attractive benefit in the conservation and preservation process. Sultan et al. (2018) did not

observe an increase in the concentration of total anthocyanins in irradiated rice meal samples at a dosage of 2.5 kGy. A similar result was obtained by D' Angelis, (2020), in which the nutritional composition, as well as the concentration of bioactive compounds, antioxidant activity, and technological properties of irradiated whole meal sorghum flours were not increased at the applied dosage of 5 kGy, however, their quality was maintained without causing changes in the macronutrients and micronutrients present. Different applications of irradiation for agro-industrial waste and the corresponding dose range are listed in Table 3.

5.3. Applications of bioactive compounds extracted from agro-industrial waste

The implementation of the use of substances extracted from agro-industrial residues in human food requires careful evaluation of their effects when absorbed by the body (Gemechu, 2020). In vitro genotoxicity and cytotoxicity tests define whether a bioactive compound extracted from a waste product can be safely and efficiently assimilated by the body and then used for consumption (Pateiro et al., 2020). In addition, the waste needs to undergo pre-treatments aimed at reducing the microbial load to ensure safety and reduce perishability without losing nutritional properties. Despite this, conventional pre-treatment methods, such as drying and washing, negatively affect the presence and quantity of bioactive compounds (Sagar et al., 2018; Shinwari; Rao, 2018; Sagar et al., 2024). In this context, ionizing radiation has stood out as a promising technique among the currently available resources. More than 60 countries worldwide have regulations that allow the irradiation of products for human consumption (IAEA, 2023).

With the population's growing interest in food bioactives that provide beneficial effects to human health and reduce the risk of disease

Table 3
Applications, doses, and effects of irradiation on agro-industrial waste.

Agro-industrial waste	Irradiation dose (kGy)	Effects	References
Pistachio shell (<i>Pistachia vera</i>)	10, 20, 30, 40, 50, and 60	Reduction in tannin content and antioxidant activity of the extracts, but increased the total phenolic content, in addition to decreasing the peel digestion rate (40 kGy)	Behgar et al. (2011)
Cassava waste pulp (<i>Manihot esculenta</i>)	10, 20, and 30	The dose of 10 kGy was the best for synthesizing hydrogels based on cassava pulp (onggok) with high absorption capacity, and stable mechanical properties	Puspita et al. (2021)
Cassava waste (<i>Manihot esculenta</i>)	500	Radiation pretreatment provides additional degradation of glucose content. The glucose yield in enzymatic hydrolysis of inside husk increases from 4.5 to 20% after being irradiated	Chosdu et al. (1993)
Corn stalk (<i>Zea mays</i> L.)	500	The glucose yield of corn stalk was 20% in untreated samples and increases to 43% after treatment with irradiation and 2% NaOH	Chosdu et al. (1993)
Lotus seed (<i>Nelumbo nucifera</i>)	2.5, 5, 7.5, 10, 15, and 30	Significant increase in ash (>10 kGy) and carbohydrates (30 kGy), with increase in phenolics and total tannins. Increase in protein solubility (>5 kGy), foaming capacity (>7.5 kGy) and least gelation capacity (>5 kGy) of seed flour	(Bhat and Sridhar, 2008)
Apricot seed (<i>Prunus armeniaca</i>)	6 and 9	Increase in the acidity index and color absorption spectrum in oil extracted from irradiated apricot seed exposed to doses of 9 kGy	(Al-Bachir and Koukdi, 2019)
Red pitaya shell (<i>Hylocereus costaricensis</i>)	1, 2, and 4	Improvement in some bioactive properties, such as increased vitamin C content, antioxidant capacity, total phenolic compounds, and maintenance of the amount of dietary fiber. The 4 kGy dose showed the best results	Santos et al. (2022)
Residue from the production of avocado oil (<i>Persea americana</i>)	5	Increased extractability of bioactive compounds from avocado peel, seed, and pulp (after oil extraction)	Barros et al. (2025)
Banana peel (<i>Musa acuminata</i>)	0.2, 0.4, 0.6, and 1	Collapse of the peel structure and delayed softening and yellowing of the fruits were induced at a dose of 0.2 kGy	Strydom et al. (1991)
Banana peel (<i>Musa acuminata</i>)	20	Production of carboxymethylcellulose/irradiated banana peel polymeric films for wastewater dye remediation	Gad et al. (2023)
Grape seeds from pomace after wine production (<i>Vitis vinifera</i>)	1, 3, 5, and 7	Grape seeds can be used as a source of edible oil. FFA and peroxide values increased with increasing radiation dose. Trans fatty acids were not detected in irradiated samples. Protection against pathogens and spoilage microorganisms, without changes in chemical composition, in doses of up to 5 kGy	Apaydin et al. (2017)
Grape seeds (<i>Vitis vinifera</i>)	3, 5, 7, 10, and 12	Sterilization of grape seeds. A radiation dose of 10 kGy is sufficient for complete bacterial inactivation	Sezer et al. (2023)
Peanut shell (<i>Arachis hypogaea</i>)	2.5 and 5	The treatment improved the antioxidant activity of the free phenolic fraction, and the irradiated peanut shells were microbiologically safe for consumption	Camargo et al. (2015)
Olive pomace (<i>Olea europaea</i>)	5, 10, 16, and 22	Improves the extractability of phenolic compounds by at least 2 times. Increased antioxidant activity in olive pomace, maintaining the ability to protect erythrocytes against oxidation-induced hemolysis	Madureira et al. (2020b)
Sugarcane bagasse (<i>Saccharum officinarum</i>)	100, 500, 1000, and 2000	Irradiation disrupts the lignocellulosic structure of bagasse, opening easy access to acids and hydrolytic enzymes for cellulosic hydrolysis, resulting in fermentable sugars	Kapoor et al. (2017)

development, irradiated waste extracts with improved bioactive properties emerge as an attractive possibility for incorporation into food products and new formulations of functional foods and nutraceuticals. Several studies involving the addition of bioactive compounds from agro-industrial waste for food, cosmetics, and pharmaceutical applications have been reported (Lemes et al., 2022).

A study published by Mildner-Szkudlarz et al. (2011) brought a new formulation of rye bread incorporated with up to 6% of by-products extracted from grape residues and presented data of improvement in antioxidant activity due to the higher values of phenolic compounds. Later, a direct method to obtain polyphenolic extracts from white grape residues with antioxidant and antibacterial properties was patented to be used on an industrial scale in the cosmetic, pharmaceutical, and food industries (Burin et al., 2014). In addition, Hallabo et al. (2018) reformulated wheat flour with 6% mango, onion, and potato peels to manufacture biscuits. The results showed that the new biscuits showed higher antioxidant activity, total carotenoids, and total polyphenols than those made with traditional wheat flour. Conceição et al. (2019) observed that the peel of camu-camu, a fruit native to the Amazon region, could be used to fortify yogurt, increasing bioactive components without significantly altering its nutritional composition and fatty acid profile.

Veloso et al. (2020) proposed the application of pomegranate epicarp extracts as functional ingredients in some confectionery products. They observed that the new formulations contained higher antioxidant activity that remained unchanged during 14 days of storage. Another relevant patent in the area of reuse of agro-industrial waste, approved in 2020, proposes the use of cheese/yogurt whey and fruit pomace to directly produce ready-to-eat extruded products, such as breakfast cereals, healthy snacks, protein nutrition bars, among others (Iqbal; Rizvi, 2023). In a comparative study between wastewater treatment with ionizing radiation and conventional treatments (or combined with radiation), it was observed that the electron beam process is second only to chlorine disinfection (Rahman and Hung, 2019). This result shows that studies with ionizing radiation are advancing, and the technology is becoming more feasible to apply on a large scale.

6. Concerns and cost-benefit

There are several benefits presented here, but the implementation of radiation technology still faces some obstacles. Among them, we can mention the main ones that have been rigorously studied, as well as some proposed action plans so that ionizing irradiation can be widely used and safely.

The first and most worrying in academia is the dissemination of erroneous information that the irradiation process causes damage to health due to the formation of toxic compounds, leading to an undue prejudice against nuclear technology (Levy et al., 2018a,b; Martins et al., 2021). Over the years, these assumptions have been refuted by increasingly refined studies (publications, national and international decision-making bodies) on the use of irradiation in food as a clean and health-free technology. Although this problem has occurred with greater frequency and intensity in past decades, currently, the dissemination of information based on scientific studies has favored the culture of acceptability in using irradiation in food (Ehlermann, 2016; 2009; Roberts, 2024). The safety assessment of irradiated food can be divided into four aspects: (1) radiological safety, (2) toxicological safety, (3) microbiological safety, and (4) nutritional acceptability. All scientific results and data on the healthiness of irradiated food products are governed by experts from different countries, such as the World Health Organization, the International Atomic Energy Agency, and the Food and Agricultural Organization (WHO/IAEA/FAO).

Another topic that was discussed involves the formation of URPs (Unique Radiolytic Products), such as 2-alkylcyclobutanones (2-ACBs), which are generated by the irradiation of products with high-fat content. These rare compounds occur due to the formation of free radicals that

lead to lipid oxidation, which would limit their application in certain conditions. However, it has been reported by the WHO, FAO, and European Union (EU) that, even in products with high lipid content, the quantities are minimal and do not present any risk to human health (EU, 2021), since the radiation dose necessary to lead to toxic changes is much higher than the doses commonly used during the irradiation of food and waste (Singh et al., 2019). Furthermore, recent studies with *in vivo* testing for genotoxicity confirmed the safety of the food irradiation process (Ehlermann, 2016; Martins et al., 2021). Nowadays, due to the enormous increase in the sensitivity of analytical methods, the existence of these URPs has become just a standard method for the detection and verification of irradiated foods on the market (Ehlermann, 2014).

Another concern is related to the high cost of acquisition and installation of irradiation plants, both for machines that use radionuclides and for electron accelerators that generate electrons and X-rays, due to the need for a large supply of electricity for the operation of these plants. For both installations, strict installation control, operation, and maintenance of the entire process are essential. These costs are mostly high, but studies show that the investment is profitable with a relatively short-term return on the capital invested since, once installed, large quantities of products can be irradiated at once (Roberts, 2014). In the past, business plans were one of the main obstacles to its expansion on an industrial scale. In an attempt to facilitate the construction of irradiation plants, groups were formed to set up cooperatives and allow the installation of an irradiation center, where the equipment is shared in order to minimize operation and maintenance costs so that everyone can take advantage of the benefits of this technology (Brasil, 2022).

7. Advantages and disadvantages of irradiating agro-industrial waste

There are several potential advantages to irradiating agro-industrial waste, such as.

- 1) Control and reduction of microbial activity: Decreasing the risk of foodborne illnesses for consumers is the most essential advantage of radiation processing technology;
- 2) Preservation of the sensorial and nutritional quality of waste;
- 3) Waste can be irradiated both fresh and frozen, allowing greater flexibility regarding storage;
- 4) No radioactive traces remain in the waste after treatment with specific radiation sources (gamma rays, X-rays, and electron beams), information that many people are unaware of;
- 5) Return of waste to the production chain, converting them into products with high added value in order to avoid disposal, accumulation, and negative environmental impact;
- 6) Irradiation facilities are environmentally friendly and safe for workers and the public.

The issues related to the disadvantages of waste irradiation are as follows.

- 1) Limitations regarding application to some types of waste, since certain substances are sensitive and degraded by the use of radiation, such as vitamins C, E, A, and B12, riboflavin, thiamine, and pyridoxine;
- 2) At high doses, chemical changes induced by irradiation in some food waste can affect the sensory attributes of the product;
- 3) Irradiation can produce certain rare byproducts, such as 2-alkylcyclobutanones, which are considered toxic in high quantities;
- 4) Irradiation may not be effective in eliminating foodborne viruses and prions, a limitation also present in other treatment methods;
- 5) Reluctant perceptions regarding the consumption of products processed by radiation;
- 6) Resistance from industry, workers, and the public to nuclear technology;

- 7) High capital cost for installing the plants, but the return can be obtained in a short period.

8. Future perspectives of irradiation

The future applications of ionizing radiation in the food production chain are both promising and multifaceted. In agriculture, techniques such as seed priming and plant hormones using low radiation doses, particularly X-rays or γ -rays, have demonstrated positive effects on seed germination, vegetative vigor, and the early accumulation of phenolics and antioxidants in certain crops (Volkova et al., 2022; Mahood et al., 2025). Moreover, directed radiation in combination with mutagenesis and genome editing represents a future frontier for optimizing crop varieties with enhanced environmental stress tolerance and higher productivity (Geras'kin et al., 2025).

In food processing and preservation, irradiation stands out for its ability to inhibit sprouting, reduce pathogenic microorganisms, and extend shelf life without compromising the sensory or nutritional quality of products (Mshelia et al., 2022). Already endorsed by WHO, FAO, and IAEA, this technology provides a safe and effective alternative to conventional practices, with considerable potential for growth as infrastructure expands and public perception improves.

Finally, in the valorization of agro-industrial residues, ionizing radiation emerges as an innovative approach to enhance by-products, promoting increased phenolic content, antioxidant activity, and efficiency in the extraction of bioactive compounds across various crops, as highlighted in the review by Madureira et al. (2020a). Other recent reviews further emphasize the potential of this technology in synergy with biorefinery processes and waste valorization strategies aimed at producing biopharmaceuticals, biopolymers, flours for human and animal consumption and high-value additives (Ito et al., 2017; Hallabo et al., 2018; Hazeena et al., 2024).

9. Conclusion

Irradiation is a nonthermal, nonchemical, environmentally clean, and energy-efficient food and waste processing technique used to extend the shelf life of fresh or processed foods by preventing contamination with harmful microorganisms while managing to preserve the organoleptic and nutritional properties. In recent decades, the use of ionizing radiation has expanded in several countries for the disinfection of pests, reduction of the microbial load in agricultural products and meat, sprout inhibition, and, more recently, it has revealed itself to be a promising technique for application to agro-industrial waste, by allowing the extraction of important bioactive compounds that can be used in new formulations, contributing not only to adding value to the raw material but also to the sustainability of the process by avoiding disposal, accumulation and negative environmental impact. Despite having great potential in the agroindustry, the application of ionizing radiation in the processing of products intended for consumption is still underestimated. Several decades of research have strived to determine the advantages versus few disadvantages of subjecting food materials to radiation, which has resulted in several international bodies, such as the WHO, IAEA, FAO, and FDA, certifying that food irradiation is a method of safe processing for the environment and human health. Still, to reach common consumers, it is essential that governments and the media exercise more trust in irradiated products so that this technology gains greater acceptability in modern society.

CRediT authorship contribution statement

J.P.A.A. Barros: Supervision, Project administration, Investigation, Conceptualization. **V. Spagnolo:** Writing – review & editing, Investigation, Conceptualization. **L.M. Rondan-Flores:** Resources, Conceptualization, Investigation. **B.G. Negrão:** Resources, Conceptualization, Investigation. **V.F. Benedetti:** Resources. **A.L.C.H. Villavicencio:**

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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